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Stimulated Brillouin scattering of elliptical laser beam in collisionless plasma

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ABSTRACT

This paper presents an investigation of self-focusing of elliptical laser beam in collisionless plasma and its effect on stimulated Brillouin scattering. The pump beam interacts with a pre-excited ion-acoustic wave leading to Brillouin back-scattered process. The transverse intensity gradient of a pump beam generates a ponderomotive force, which modifies the background plasma density profile in a direction transverse to pump beam axis. This modification in density effects the incident laser beam, ion-acoustic wave and back-scattered beam. Non-linear differential equations for the beam width parameters of pump laser beam, ion-acoustic wave and back-scattered beam are set up and solved numerically. It is observed from the analysis that the focusing of waves enhances the SBS back-reflectivity.

1. Introduction

The interaction of intense laser beams with plasma is a active field of research due to its importance in laser driven fusion [1–4]. It is well established that various laser-plasma instabilities like self-focusing, harmonic generation, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), etc. [5–12], come into existence during the interaction of laser pulses with plasmas and play significant role as far as the transfer of energy from laser to the plasma is concerned. The presence of these instabilities results in the significant loss in the incident laser energy, which leads to poor laser plasma coupling. These instabilities can also modify the intensity distribution, affecting the uniformity of energy deposition. In particular, SBS governs the amount of laser energy that can be propagated over long distances through plasma. Control of SBS is crucial in the context of laser-driven inertial confinement fusion (ICF). In SBS, the incident electromagnetic wave (EM) resonantly decays into scattered EM wave and an ion-acoustic wave (IAW). The beating between the incident and Scattered EM waves reinforces the density perturbation, thus leading to unstable loop. As a result, SBS can lead to scattering of a significant portion of the incoming laser light and thus prevent an efficient coupling of the laser light with the target. Since, many laser matter interaction applications such as advanced radiation sources, laser fusion, and relativistic nonlinear optics depend critically on the amount of transmitted laser energy through the plasma. Consequently, SBS is studied both experimentally and theoretically. In solid target experiments, energy reflectivities attributed to SBS have varied from 0 to 50% [13–16]. There is a vast difference between the reported results of theory and experiments in spite of intensive research work done on studies of SBS during the last two decades [17–20]. This mismatch between the results of theory and experiment may be due to the idealized theoretical assumptions made in the theory. Theoretical explanation of low reflectivity observed in large scale fusion experiments [21–25] is one of the main challenge for theoretical researcher.

In most of the theoretical investigations on non-linear phenomena self-focusing and stimulated back scattering have been carried out separately by ignoring the interplay among them. In order to understand the interplay among various instabilities, it is very important to investigate the evolution of these instabilities in the nonlinear regime, where they co-exist and effect each other. In light of considerable current interest in self-focusing and Brillouin scattering, a lot of work has already been done in the past [26–30]. The fundamental works on the nonlinear propagation of laser beam in different media have been carried out by taking cylindrical gaussian beams [31,32]. Since many laser systems produce a beam, which is more nearly elliptical than circular in cross-section and it has been observed that the focused elliptically polarized light for the semiconductors is crucial for creation of photoinduced nonlinear optical effects [33]. It is therefore worthwhile to study this practical situation. So our motivation of present work is to study the effect of self-focusing of elliptical laser beam on the Brillouin scattering process in collisionless plasma.

In the present paper, Brillouin Scattering of a elliptical laser beam from a collisionless plasma has been investigated. The pump wave (ω_0, k_0) interacts with pre-excited ion-acoustic wave (ω,k) to generate a scattered wave ($\omega_0-\omega$, k_0-k). As a specific case, back scattering for which $k \simeq 2k_0$ has been discussed. The pump beam exerts a ponderomotive force on the electrons, leading

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to redistribution of carriers and consequently, the pump beam becomes self-focused. The dispersion relation for ion-acoustic wave is also significantly modified. The phase velocity of the ion-acoustic wave becomes minimum on the axis and increases away from it. Therefore, if appropriate conditions are satisfied, the ion-acoustic wave may also get focused. Since the scattered intensity is proportional to the intensities of the pump and ion-acoustic wave, it is therefore expected that the self-focusing should lead to enhanced back-scattering.

In Section 2, solution of the wave equation for the pump wave is derived in the paraxial ray approximations. Differential equations for the beam width parameters of the pump wave are also derived. In Section 3, the wave equation for the ion-acoustic wave is solved in the paraxial ray approximation and differential equations for the beam width parameters of the ion-acoustic wave are also derived. In Section 4, the wave equation for the back-scattered wave is solved in the paraxial ray approximation and differential equations for the beam width parameters of the back-scattered wave are also derived. Expression for the reflectivity 'R' of the back-scattered beam is also derived. Finally, a detailed discussion of the results is presented in Section 5.

2. Solution of wave equation for pump wave

Consider the propagation of high power elliptical gaussian laser beam of frequency ω_0 and wave number k_0 in a collisionless plasma along z-axis. The transverse intensity distribution of an elliptical laser beam along the wave-front at $z=0$ is given by

$$E_i E_i^\star|_{z=0} = E_{00}^2 \exp\left[-\frac{x^2}{a_0^2}-\frac{y^2}{b_0^2}\right] \tag{1}$$

where a_0 and b_0 are the initial dimensions of the laser beam at $z=0$ in x and y directions respectively, E_i is the electric field vector of pump beam and E_{00} is the axial amplitude of the beam.

The transverse intensity gradient generates a ponderomotive force, which leads to modification in the background electron density (N_0). Following Sodha et al. [32] the electron density N_{oe} in the presence of laser beam may be written as

$$N_{0e} = N_0 \exp\left[-\frac{3}{4}\alpha\frac{m}{M}E_i E_i^\star\right] \tag{2}$$

where the non-linearity parameter α is given by

$$\alpha = \frac{e^2 M}{6k_B T_0 \gamma m^2 \omega_0^2} \tag{3}$$

where N_{oe} is the modified electron density in the presence of laser beam, N_0 is the electron density in the absence of beam, e and m are the charge and mass of plasma electrons. k_B is Boltzmann's constant, $\gamma = 3$ is the ratio of specific heats for electron gas, and T_0 is the equilibrium plasma temperature, M is the mass of ion.

The wave equation governing the electric field E_i of the pump laser in plasma can be written as

$$\nabla^2 E_i + \frac{\omega_o^2}{c^2}\left[1-\frac{\omega_p^2 N_{0e}}{\omega_o^2 N_0}\right]E_i = 0 \tag{4}$$

Now, following Akhmanov et al. [31] and Sodha et al. [32], the solution of E_i can be written as

$$E_i = E_0 \exp[i(\omega_0 t - k_0(S_0+z))] \tag{5}$$

$$E_o^2 = \frac{E_{oo}^2}{f_{01}f_{02}} \cdot \exp\left[\frac{-x^2}{a_o^2 f_{01}^2}\right]\exp\left[\frac{-y^2}{b_o^2 f_{02}^2}\right] \tag{6}$$

$$S_o = \frac{1}{2}x^2\frac{1}{f_{01}}\frac{df_{01}}{dz} + \frac{1}{2}y^2\frac{1}{f_{02}}\frac{df_{02}}{dz} + \Phi_o(z) \tag{7}$$

$$k_0 = \frac{\omega_0}{c}\epsilon_0^{1/2} \tag{8}$$

where E_0 is the real function of x, y and z. S_0 is the eikonal for the main beam, $\Phi_0(z)$ is a constant whose value will not be required explicitly in further analysis. ϵ_0 is the linear part of the dielectric constant, c is the speed of light, ω_p is the plasma frequency, f_{01} and f_{02} corresponds to dimensionless beam width parameters of pump beam and satisfy the following differential equations:

$$\frac{d^2 2f_{01}}{dz^2} = \frac{1}{k_0^2 a_0^4 f_{01}^3} - \frac{\omega_p^2}{\omega_0^2\varepsilon_0} \cdot\left(\frac{3}{4}\alpha\frac{m}{M}E_{00}^2\right)\exp\left(-\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{f_{01}f_{02}}\right)\frac{1}{a_0^2 f_{01}^2 f_{02}} \tag{9}$$

$$\frac{d^2 f_{02}}{dz^2} = \frac{1}{k_0^2 b_0^4 f_{02}^3} - \frac{\omega_p^2}{\omega_0^2\varepsilon_0} \cdot\left(\frac{3}{4}\alpha\frac{m}{M}E_{00}^2\right)\exp\left(-\frac{3}{4}\alpha\frac{m}{M}\frac{E_{00}^2}{f_{01}f_{02}}\right)\frac{1}{b_0^2 f_{02}^2 f_{01}} \tag{10}$$

where $f_{01}=f_{02}=1$ and $df_{01}/dz = df_{02}/dz = 0$ at $z=0$. Eqs. (9) and (10) describe the change in the dimensionless beam width parameters f_{01} and f_{02} of pump beam on account of the competition between diffraction divergence terms and nonlinear refractive terms as the beam propagates in the collisionless plasma.

3. Solution of wave equation for ion-acoustic wave

The laser beam interacts with the ion-acoustic wave and leads to its excitation. To analyze the excitation process of ion-acoustic wave in the presence of ponderomotive non-linearity. We start with the following set of fluid equations [34].

Continuity equation:

$$\frac{\partial n_{is}}{\partial t} + \nabla\cdot(N_0 V_{is}) = 0 \tag{11}$$

Momentum equation:

$$\frac{\partial V_{is}}{\partial t} + \frac{\gamma_i v_{th}^2}{N_0}\nabla n_{is} + 2\Gamma_i V_{is} - \frac{e}{M}E_{si} = 0 \tag{12}$$

where n_{is} is the perturbation in the ion density, V_{is} is the velocity of ion-fluid, v_{th} is the ion-thermal velocity, γ_i is the ratio of specific heat of ion-gas, Γ_i is the landau damping factor of the ion wave, E_{si} is the electric field associated with the generated ion-acoustic wave, satisfying the poisson's equation

$$\nabla\cdot E_{si} = -4\pi e(n_{es}-n_{is}) \tag{13}$$

Where n_{es} and n_{is} corresponds to perturbations in the electron and ion densities, and are related to each other by following equation:

$$n_{es} = n_{is}\left[1+\frac{k^2\lambda_d^2}{\frac{N_{0e}}{N_0}}\right]^{-1} \tag{14}$$

where k is the propagation constant for ion-acoustic wave, $\lambda_d = \sqrt{k_B T_0/4\pi N_0 e^2}$ is Debye length. The landau damping coefficient Γ_i for IAW is given by [35] $2\Gamma_i = k/(1+k^2\lambda_d^2)\sqrt{\pi k_B T_e/8M}$ $[\sqrt{m/M}+\sqrt[3]{T_e/T_i}\exp(-(T_e/T_i)/(1+k^2\lambda_d^2))]$, where T_e and T_i are the electron and ion temperatures.

Following standard techniques, equation for the space time evolution of perturbation in the ion density can be obtained as

$$\frac{\partial^2 n_{is}}{\partial t^2} + 2\Gamma_i\frac{\partial n_{is}}{\partial t} - \gamma v_{th}^2\nabla^2 n_{is} + \omega_{pi}^2\frac{N_{0e}}{N_0}\frac{k^2\lambda_d^2}{1+k^2\lambda_d^2}n_{is} = 0 \tag{15}$$